Modeling of Cloud-top Entrainment

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LONG TERM GOALS

Our long term goals are to understand the dynamics of atmospheric motions on scales of order 10 m - 10 km in sufficient detail to be able to provide a consistent subgrid scale turbulent closure for models across a range of scales, and to be able to utilize simulated variances as a measure of forecast predictability.

OBJECTIVES

The chief objective of the present grant is to better understand the physical processes which control the magnitude of entrainment fluxes of heat and moisture across the capping inversion of the atmospheric boundary layer, and to formulate a closure model for cloud-top entrainment that is consistent for a broad range of boundary layer conditions and forcings. Ideally, this closure model would allow one to produce a simulation at any desired level of resolution, with the results of lower resolution simulations being approximately similar to results obtained by appropriate spatial filtering of the higher resolution simulation.

APPROACH

This research involves the utilization of the high resolution turbulent transport codes developed under previous ONR support. Our principal approach is to employ large eddy simulations (LES) to conduct controlled numerical studies of the effects of different boundary layer forcings and conditions (initial temperature and moisture profiles, surface heat and moisture fluxes, cloud-top radiation, wind shear, etc.) on the boundary layer dynamics, cloud structures and, in particular, entrainment rates, which result. The understanding and quantitative correlations gained can be used to better incorporate these effects into the subgrid parameterizations utilized in lower resolution models.

WORK COMPLETED

During the past year we have performed extensive LES studies of cloud-top entrainment in order to quantitatively extend the results of Lewellen and Lewellen 1998 (hereafter referred to as LL98).

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These include variations of the inversion capping strength and structure, shear within the inversion and within the boundary layer, surface heat and moisture fluxes, and nonuniform surface heating to explore the effects of changing the boundary-layer eddy structure.

In addition, we have continued our participation in inter-model comparisons under the coordination of the GCSS (GEWEX Cloud Systems Studies) boundary layer cloud modeling working group.

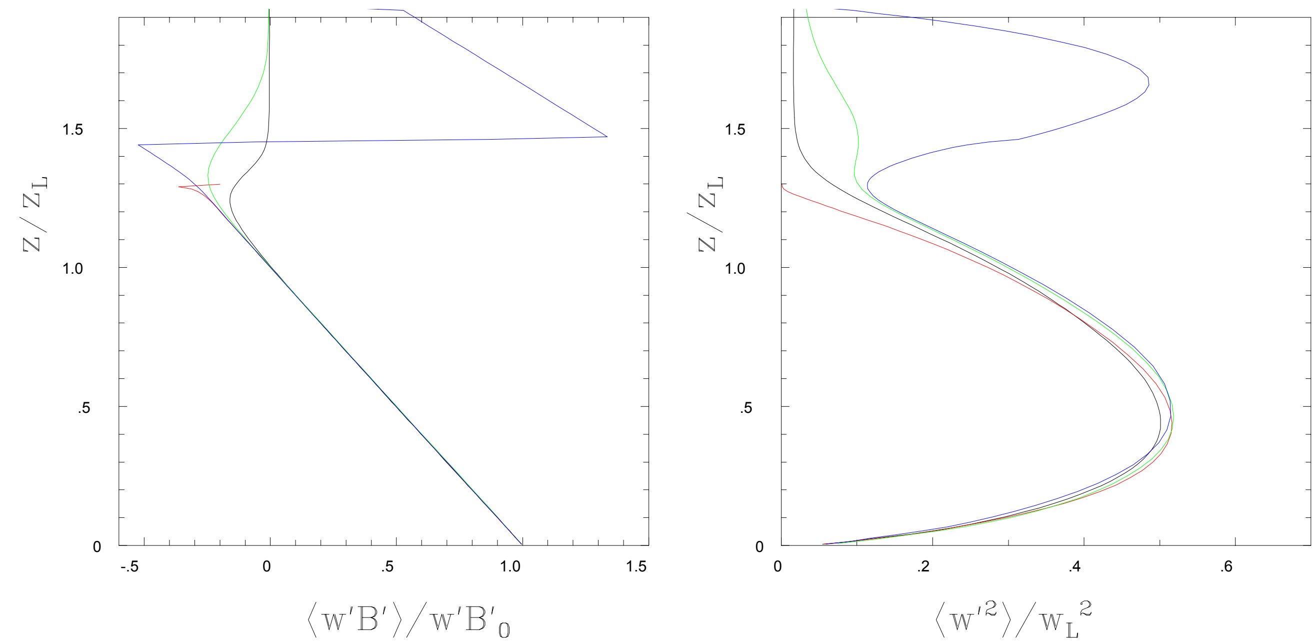
RESULTS

One of the chief difficulties in comparing boundary layer entrainment results is the ambiguity encountered in defining properties such as the boundary layer height, z_i, entrainment velocity, entrainment heat flux, and inversion temperature jump for cases with different surface forcings, capping strengths, lapse rate above z_i, inversion thickness, etc. For example, different definitions of z_i (e.g., the height at which the temperature flux has its minimum, or where the temperature gradient is largest) can lead to different values deduced for the entrainment rate, particularly for weak inversions, and account for much of the variability in entrainment results quoted in the literature for the convective boundary layer.

In LL98 we presented evidence that for quasi-steady, tightly capped, buoyantly driven layers, the boundary layer scale eddy dynamics sets the entrainment rate independent of the detailed properties of the inversion. Consistent with this result, for dry, quasi-steady, convective dynamics, we can use well measured parameters within the boundary layer -- the heat flux at the surface and its slope within the mixed layer -- to scale our LES results rather than some measure of z_i based upon the inversion structure. We have found that this gives a successful scaling of the vertical profiles within the boundary layer for these cases even for radically different properties within the inversion and above the boundary layer (e.g., fig.1). This allows us to extend the results of LL98 to weakly capped boundary layers. The cases considered include ones with strong or weak capping inversions, with and without modest wind shear, cases with a second buoyantly driven mixed layer above the primary one, and cases with a top lid with a heat flux forced through it. In those cases, such as the last two categories, where a natural mixed layer height is easily identified, the scaled values for that height agree. In the purely buoyantly driven layers the scaled integrated buoyancy fluxes within the layers agree -- a direct consequence of having the same entrainment efficiency (as defined in LL98) in all of these cases.

When strong shear is added at the top of the boundary layer, three additional effects can come into play as illustrated in figure 2: another significant energy source, shear production, appears; the inversion gradients as well as the inversion height can change significantly over time; and the shear dynamics can exhibit a strong intermittency or periodicity. The convection in the boundary layer leads to steady entrainment which sharpens the inversion temperature and velocity gradients. This increases the level of shear instability locally in some regions, touching off short periods of intense shear production. The resultant mixing reduces the gradients, in turn reducing the level of instability, whereupon the cycle may repeat. Using the boundary layer scaling described above, and assuming that the entrainment flux transport into the mixed layer itself is governed by the buoyantly driven boundary layer scale eddies in the same way as in the absence of large shear, we can infer what portion of the negative buoyancy flux representing entrainment is a result of the shear production. We have found for different shear cases, as well as for different time periods (following the intermittency) within a given case, that the ratio of the entrainment buoyancy flux attributable to shear to the shear production (i.e., the appropriately defined flux Richardson number) is fairly constant with a value near 1/4. This is for shear production within the

inversion region; we find shear production within the boundary layer or near the surface to be far less efficient in driving entrainment.

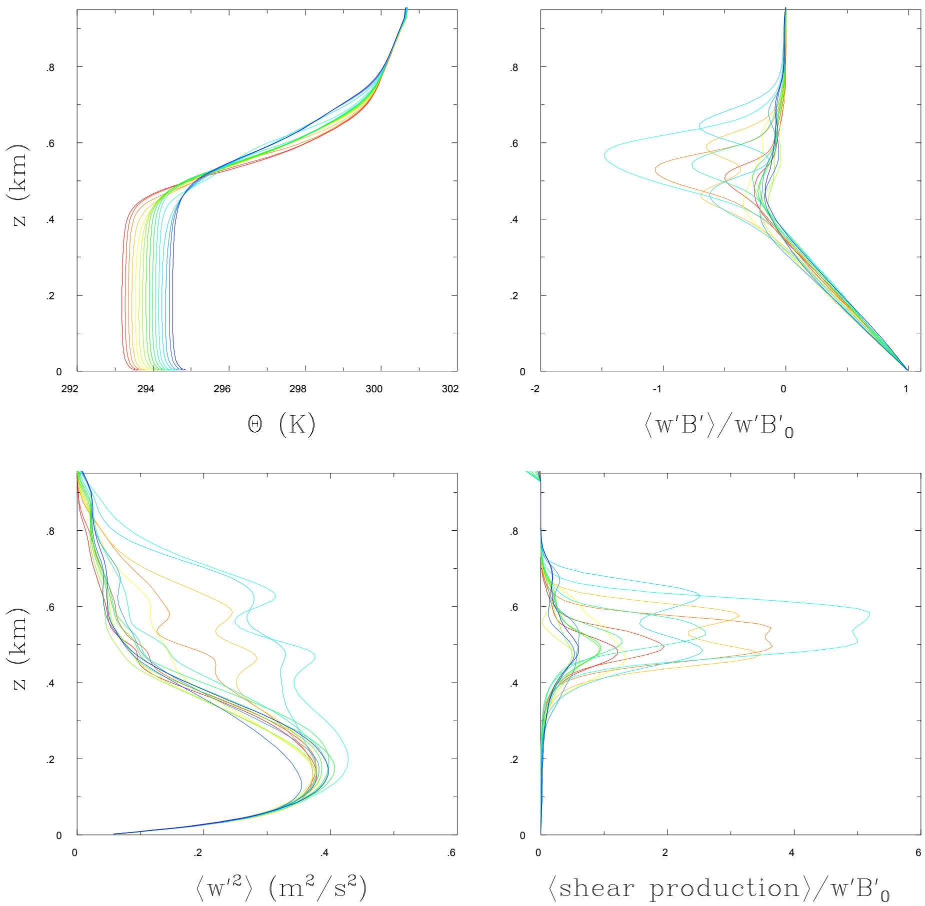


1. Mean vertical profiles of buoyancy flux and vertical velocity variance for different cases, nondimensionalized using the surface buoyancy flux $w'B'_o$, and magnitude of the buoyancy flux slope in the mixed layer, S_B, ($z_L = w'B'/S_B$; $w_L = (w'B'_o\, z_L)^{1/3}$. Black – weakly capped layer; red – capped by rigid lid; blue – second buoyantly driven mixed layer above the first; green – shear across inversion.

These results are consistent with the picture given in LL98 of boundary layer scale eddy dynamics controlling the overall entrainment rate; it remains to determine the sensitivity of that rate to changes in the large eddy dynamics. In a separate series of investigations we have employed different patterns of nonuniform surface heating to alter the structure of the boundary layer scale eddies and explore this dependence for different capping conditions. Preliminary results show that significantly changing the large eddy structure, for example to the highly skewed dynamics characteristic of surface latent heat driven boundary layers, can significantly change the entrainment efficiency, though once again apparently independently of the details of the inversion structure.

IMPACT/APPLICATION

A consistent quantitative model of cloud top entrainment is important to any model which involves cloud dynamics. In addition to the Navy's operational forecasting interest in clouds, an understanding of cloud dynamics on this scale is also a central issue in modeling global climate change. We expect this effort to lead to improved subgrid parameterization of entrainment in models such as the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) regional model developed at the Naval Research Laboratory (Hodur, 1997).



2. A sequence of ten minute averaged mean vertical profiles for a convective boundary layer with strong shear across the inversion, progressing in time from red to blue.

TRANSITIONS

None

RELATED PROJECTS

The LES code developed under ONR support has been modified and used to model aircraft wakes/contrails for NASA (Lewellen and Lewellen, 1999), and to model the turbulent interaction of a tornado with the surface for NSF (Lewellen et al. 1999). The use of essentially the same LES code on these separately supported efforts works to the advantage of all three projects, particularly in fostering numerical improvements in the efficiency and accuracy of the code.

REFERENCES

Hodur, Richard M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Monthly Weather Review*, Vol. 125, 1414-1430.

Lewellen, D.C., and W. S. Lewellen, 1998: Large-Eddy Boundary Layer Entrainment. *J. of the Atmospheric Sciences*, Vol. 55, 2645-2665.

Lewellen, D. C., and W. S. Lewellen, 1999**:** Effects of aircraft wake dynamics on contrail development. NASA 1999 Conference on the Atmospheric Effects of Aviation, April 19 – 22, Virginia Beach, VA.

Lewellen, D. C., W. S. Lewellen, and J. Xia, 1999: The Influence of a Local Swirl Ratio on Tornado Intensification near the Surface. In press *J. of the Atmospheric Sciences.*

PUBLICATIONS

Bretherton, C., M. MacVean, P. Bechtold, A. Chlond, W. Cotton, J. Cuxart, H. Cuijpers, M. Khairoutdinov, B. Kosovic, D. Lewellen, C-H. Moeng, P. Siebesma, B. Stevens, D. Stevens, I. Sykes, M. Wyant, 1999: An intercomparison of radiatively-driven entrainment and turbulence in a smoke cloud, as simulated by different numerical models. *Quart. J. Roy. Meteor. Soc.,* Vol. 125*,* 391-423.

Stevens, B., B. Albrecht, J. Cuxart, E. Sanchez, A. Brown, M. MacVean, A. Lock, P. Duynkerke, P. Siebesma, H. Jonker, A Ackerman, A. Chlond, D. Lewellen, and D. Stevens, 1999: Cloud fraction and trade cumulus: an LES intercomparison study. Proceedings of the AMS 13th Boundary Layer Turbulence Conference, Jan. 11 – 15, Dallas, TX.